The Swimming Speed of Adult Pink Salmon, *Oncorhynchus gorbuscha*, at 20° C and a Comparison with Sockeye Salmon, *O. nerka*

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ABSTRACT

Brett, J. R. 1982. The swimming speed of adult pink salmon, Oncorhynchus gorbuscha, at 20°C and a comparison with sockeye salmon, O. nerka. Can. Tech. Rep. Fish. Aquat. Sci. 1143: iii + 37 p.

Prolonged swimming speeds of female pink salmon (55 cm, 1879 g) were determined in a 27-cm diameter steel tunnel at 20±1°C. The speeds were corrected for cross-sectional blocking effect of the fish by comparing tailbeat frequencies for the same velocities in the tunnel and in an open flume. The mean maximum sustained speed (10-hr test time) was 1.12 m/sec (2.04 L/sec). Compared with sockeye salmon, pink salmon could only perform at about 80% of the level of prolonged speed achieved in the same tunnel by sockeye of comparable size.

Key words: salmon, swimming speeds, swimming tunnel.

RÉSUMÉ

Brett, J. R. 1982. The swimming speed of adult pink salmon, Oncorhynchus gorbuscha, at 20°C and a comparison with sockeye salmon, O. nerka. Can. Tech. Rep. Fish. Aquat. Sci. 1143: iii + 37 p.

On a déterminé les vitesses de nage prolongée, à 20 ± 1°C, de saumons roses femelles (55 cm, 1879 g) dans un tennel d'acier de 27 cm de diamètre. On a corrigé les vitesses de nage des poissons pour ce qui est du "cross-sectional blocking effect", en comparant les fréquences du mouvement de la queue aux mêmes vélocités dans le tunnel et dans une auge découverte. La vitesse moyenne maximale maintenue pendant la période d'essai de 10 heures s'élève à 1,12 m par sec (2,04 L par sec). Quand on le compare au saumon rouge de taille semblable, le saumon rose ne fonctionne qu'à 80% du niveau de nage prolongée obtenu au cours d'essais dans ce même tunnel.

Mots-clés: saumon, vitesse de nage, tunnel de nage.

I. INTRODUCTION

A recent proposal by the Canadian National Railway Company (CNR) to build a second track along the Fraser and Thompson rivers in British Columbia has raised questions concerning the impact that encroachments would have on river velocities and the possible consequences to migrating salmon (Lister 1981). Up to 700 intrusions on the river could occur.

Since the building of fishways at Hell's Gate in the Fraser Canyon, pink salmon (Oncorhynchus gorbuscha) have gradually expanded their range up the Fraser River and into the South Thompson River (Ward 1959). This species is considered to be less capable as a swimmer than the four other indigenous species of Pacific salmon, not only because of its smaller average size but also for behavioral and possibly physiological reasons. No systematic studies of prolonged swimming speeds have been performed on pink salmon. Beamish's (1978) review of swimming speeds of fish reveals only one publication, from a Russian source (Krykhtin 1964; reported in Malinin 1973), related to a set of observations on pink salmon cruising speeds.

This report deals with a study carried out in 1963 while conducting more extensive tests on the swimming energetics of sockeye salmon, O. nerka (Brett 1964, 1965, 1967, 1973; Brett and Glass 1973). Insofar as possible all the data on pink salmon have been assembled in order to respond to the need for information engendered by the CNR twin-tracking program. It also brings to light an additional set of comparative data on salmon swimming speeds not previously reported. Comparison with sockeye salmon is made.

FISH SWIMMING SPEEDS

Before describing the research it is desirable to outline the basic principles of studying swimming speeds, and the definition of the terms employed.

Fish are capable of swimming continuously for great distances and extended time periods. Maturing adult salmon returning to spawn cover thousands of ocean and river miles, and may maintain continuous upstream migration for a month or more in large rivers. Such performance is termed sustained swimming. On demand, energy and oxygen can be supplied to the muscles on a more-or-less continuous basis. At some point of increased velocity, supply cannot meet demand and the fish is limited in the time it can maintain the corresponding higher speed. Because periods of a number of hours may be involved, this performance is termed prolonged swimming. The transition point between sustained and prolonged is identified as the maximum sustained speed (see: Brett 1964; Webb 1975; Beamish 1978). For relatively high velocities, a fish resorts to quick, short darts or sprints. This is called burst swimming, and can rarely be maintained for more than half a minute or so (Bainbridge 1960).

The basic performance curve relating swimming speed to fatigue-time is determined for individual fish (swimming singly or in groups) by exposing them to fixed water velocities and recording the time-to-fatigue (Fig. 1). The linear resolution of the curve as an exponential function serves to identify the transition points distinguishing sustained, prolonged and burst speeds. The time-limit for testing low velocities in the region of sustained speeds has to be set arbitrarily from experience with the species concerned; it is usually not in excess of 6-10 hr. At the upper extreme of velocities, involving short burst speeds, special apparatus and techniques are required to develop and record the speed and times involved (Bainbridge 1958, 1960; Paulik 1959). Burst speeds were not determined in the present study.

Many factors affect swimming ability of fish--in particular form, size and temperature. In general, the more streamlined the better the swimmer; the larger the fish the higher the sustained swimming speed; and, the higher the temperature (up to an optimum) the faster the fish can swim. Because of the size effect, and comparisons of the relative swimming speeds of fish, speeds are often expressed in terms of body lengths traversed per unit time (L/sec). Care has not always been taken to distinguish between length measurements as total, fork, or standard length. Sometimes the erosion of the caudal fin makes total length difficult to determine accurately. Nevertheless, it is this dimension that should always be measured or estimated; a fish's propulsion is a total-length phenomenon.

An alternative method of examining swimming speed capacity is to apply stepwise increases in velocity, each lasting for a prescribed interval of time, usually about 1 hr, with the whole sequence lasting 6-8 hr. The final increment of velocity that causes fatigue is used to determine the critical swimming speed; for small fish this provides a near approximation of the maximum sustained speed (Brett 1964). The method is experimentally conservative of fish and total test-time, but lacks the precision and greater insight developed by the complete fatigue curve. Further reference to critical speeds is made in the text.

II. MATERIALS AND METHODS

1. THE SWIMMING TUNNEL

A 27 cm diameter (OD) steel pipe was inserted through the bottom stoplog of a 4 m high dam in Robertson Creek, Alberni, British Columbia. The pipe extended out for a distance of 10 m alongside an experimental flume downstream from the dam (Fig. 2). Butterfly control valves (Fig. 3) were inserted at the 5 m and 9 m positions. Centrally, between these points, a 1.5 m long fish chamber was incorporated, with acrylic plastic viewing ports (Fig. 4, 5). Immediately upstream and downstream from the chamber, short fibreglass sections were installed; these were equipped with closely spaced, vertical, aluminum vanes to improve the directional flow of water and, in the

case of the downstream vanes, to provide an electrified screen to stimulate the fish to swim maximally. A peak water velocity of 2.8 m/sec could be obtained in the tunnel. Applied velocities ranged from 0.75 to 1.74 m/sec. These were checked by use of a standardized Ott current meter.

2. THE FISH

Pink salmon do not normally occur in the Stamp-Somass River system, of which Robertson Creek is a tributary. They were trucked in loads of 20 fish from the Cheakamus River, located in the lower British Columbia mainland, and held in tanks for 2-5 days prior to testing during the period September 3 to 25. Robertson Creek temperatures averaged 20 $\pm$1°C.

From the 120 fish obtained, 68 females were selected for healthy appearance, devoid of any flesh wounds or fungus infections. Females were chosen because of the pronounced morphological changes that males undergo in the final stages of maturation. Mean lengths were: 54.98$\pm$2.45 cm SD (total length), and 45.06$\pm$2.16 cm SD (standard length). Mean wet weight was: 1,879$\pm$356 g SD (Table 1). They were mostly held in a series of 4,000-L fibreglass tanks adjacent to the tunnel.

3. EXPERIMENTAL TECHNIQUE

Individual fish were dipnetted to the water surface and carried to the tunnel chamber in a waterproof canvass bag in the form of a longitudinally folding stretcher. No anaesthetic was used. They were allowed to adapt at a reduced velocity of 0.3 m/sec for 1 hr, and then raised directly to the prescribed velocity. A bright light over the tunnel was used, with the upstream part of the chamber shaded - which was frequently used by the fish as cover. A low charge of about 3-4 V AC (60 cycle) was applied initially and raised to 10 V subsequently as needed, usually in the last 30 min of performance. If a fish maintained position above the electrified screen for 10 hr, the test was terminated; the fish was considered to be performing at a sustained swimming speed. Eleven such cases occurred (16%). Although catching and handling each fish was reduced to a minimum (less than 1 min from holding tank to swimming chamber), the fish were greatly excited and darted to and fro when first introduced into the test chamber. From experience with various adaptation times, and the fact that a full day had to be allowed for testing any given fish, an introductory hour at a low cruising velocity was adopted as the best working strategy. Overnight experience in the chamber did not appear to improve performance of adults. By comparison with sockeye salmon behavior, pinks were less reactive and more prone to laxity in swimming effort, sometimes rolling over on their side or back in the chamber. Such behavioral problems account for considerable variability in response at one and the same velocity. However, the method of using probit analysis (see Results), adopted from toxicology studies, helps to resolve the analytical problem of dealing with a scattering of poor performers.

4. SWIMMING SPEED CORRECTION

The confinement of a tunnel increases the swimming load because of cross-sectional volume displacement by the fish (solid blocking) resulting in acceleration over the body surface; there is additional interference thought to come from wall effect reducing the tail thrust (Webb 1975). Maximum cross-sectional area of an average pink salmon was calculated at 61.3 cm^2 (see dimensions in Table 1). This equalled 12.1%* of the cross-sectional area of the steel pipe (ID = 25.5 cm). In previous studies on sockeye, referred to in Brett and Glass (1973), adjustment for any tunnel effects was determined by counting tail-beat frequencies for fixed velocities in an open flume (Fig. 6) where the cross-sectional displacement was less than 1%. Flume velocities were monitored with the same standardized Ott meter. Starting from a low velocity (15 cm/sec), the velocity was increased to just under the maximum sustained speed (170 cm/sec). The velocity in the tunnel was then plotted against the velocity in the flume for equal tail-beat frequencies (Fig. 7). The corrected test-velocities could then be read off and transposed, as recorded in Table 1. The tail-beat frequency of pink salmon is displayed in relation to the corrected velocity in Fig. 8.

III. RESULTS AND DISCUSSION

1. PINK SALMON PROLONGED SWIMMING SPEEDS

To compare swimming speeds of fish that are in the same general length range (in this case 55.0±4.9 cm 2SD) but differ individually, the tunnel velocities were converted from cm/sec to L/sec (Table 1). These speeds were then arranged in modal groups of ±0.2 L/sec starting at 1.5±0.2 L/sec and increasing in increments of 0.4 L/sec to 2.7±0.2 L/sec. The order-of-fatigue in probits was plotted against the logarithm of time (Fig. 9). This provides a linear transformation of the data from which estimates of the geometric mean time-to-fatigue and variance can be determined, despite the problem of accounting for some fish in each velocity group still swimming at the end of the test time (600 min)--see discussion in Brett (1964, 1967).

The mean time-to-fatigue at any given velocity corresponds to the time-to-50% fatigue. This was plotted against the tunnel swimming speed (Fig. 10) to provide the segment of the fatigue curve related to prolonged swimming speeds (as in Fig. 1). The uncorrected maximum sustained speed of

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*At the point of maximum cross-section of the fish, this would be equal to the mean velocity increase experienced. Extending this example of solid blocking, a fish that occupied half the cross-sectional area of the tunnel would double the water velocity over its body at the widest point.

1.36 L/sec in the tunnel occurred at the limit of test time of 600 min. For comparison the fatigue-times for 10% of the sample are plotted in Fig. 10. These provide a better measure of the velocities that the majority of fish would be able to achieve for the times indicated. By use of the graph developed in Fig. 7 the tunnel velocities were transformed into the equivalent flume velocities labelled "corrected velocity" at the top of Fig. 10. The free-swimming maximum sustained speed for pink salmon at 20°C becomes 1.12 m/sec (2.04 L/sec) at the 50% fatigue level, and 0.75 m/sec (1.36 L/sec) at the 10% fatigue level.

2. COMPARISON WITH SOCKEYE SALMON

As stated, adult sockeye salmon from the Stamp River were tested in the same tunnel, and reported on by Brett (1967). Their performance was consistently higher than that of pink salmon despite a slightly smaller mean total length of 54.0 cm (1,750 g), but at a somewhat lower temperature of 18°C (Table 2). The same velocity correction can be applied to the sockeye since their size was not particularly different from the pink salmon (average of 2% shorter). The maximum sustained swimming speed was 1.33 m/sec or 2.5 L/sec for corrected velocity. This is approximately 19% faster than the pink salmon, a difference that was maintained throughout the range of prolonged swimming speeds (Fig. 10).

Unlike the pink salmon sample, both male and female sockeye were tested. They were still in a silvery state and not greatly sex-differentiated morphologically. As can be seen from Fig. 11, which is a plot of individual fatigue times, no distinction in performance can be made between sexes at that stage of maturity.

3. OTHER SOCKEYE SWIMMING SPEEDS

Brett and Glass (1973) reported on the maximum 60-min sustained speeds (also referred to as critical speeds) of maturing adult sockeye tested in a tunnel respirometer with an inside diameter of 7 in (17.8 cm). The speeds had been corrected for blocking effect by reference to the tailbeat frequency equivalents in the aforementioned open flume. At 20°C, seven adults that had a mean length of 57 cm were recorded as having an average critical speed of 130 cm/sec or 2.28 L/sec. This may be compared with the corrected 60-min sustained speed of 172 cm/sec (3.25 L/sec) derived in the larger steel tunnel reported here. The difference is considerable (30% more). In contrast, at 15°C, a single record of 178 cm/sec for a 54-cm sockeye is more in keeping with expected.

In the same paper a predictive graph in the form of isopleths of swimming speed in relation to temperature and body length was developed (Fig. 12), drawn from a composite of all experimental data. The difference between predicted and observed was only 5% (less) for the large tunnel tests and 27% (more) for the smaller, respirometer tunnel. The single record at

15°C for an adult sockeye in the smaller tunnel was within 4% of the predicted. Aside from the fact that different apparatus was used, the comparison brings out an inconsistency in reporting by Brett and Glass (1973). The term "maximum 60-min sustained speed" is actually a misnomer, since sustained speeds are those of longer duration (theoretically to infinity). It refers instead to the prolonged swimming speed corresponding to the 60-min time interval. Critical speeds derived by Brett (1964, 1967) happened to be those for 60-min duration, the final increment of velocity being calculated as the maximum that could be sustained for such an interval (hence the misnomer). Farlinger and Beamish (1977) examined the effect of different time and velocity increments on the critical swimming speed of largemouth bass (Micropterus salmoides). Critical speed fell off exponentially with increasing time increments. Beamish (1978) considered that 200 min would be sufficient to enter the sustained swimming category. This has been shown by Brett (1967) to be size-dependent, requiring no more than 120 min for fingerlings and extending to 500-600 min for adults. This means that both critical speeds and 60-min prolonged speeds do not have a constant relation to maximum sustained speed because of size effect. The isopleths in Brett and Glass (1973) (Fig. 12) should be considered as the 60-min prolonged speeds with confidence limits of approximately ±10%. Again, it should be emphasized that the speeds apply to the "median fish" performance capability--the 50% fatigue level. Safeguards for a population would have to apply to some lower value, possibly the 10% fatigue threshold, thereby allowing for the influence that some poor performers in the artificial, experimental environment undoubtedly have on depressing the fatigue curve.

Fig. 12 is reproduced here with a suggested swimming speed scaling factor of 0.8 for pink salmon relative to sockeye, on the presumption that the difference obtained with adults applies to smaller sizes, and relates to temperature in a similar manner for the two species. This scale applies only to the 60-min prolonged speed and to the expected mean performance (50%). It provides a provisional model for pink salmon which can be tested for applicability by checking selected points on the isopleths for reliability.

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Table 1. Length-weight relations, swimming speeds, and times-to-fatigue for adult female pink salmon tested at 20 ±1°C. Corrected velocities (last column) are those derived as stated in text.

Total length (cm)	Standard length (cm)	Maximum width (cm)	Maximum depth (cm)	Weight (g)	Applied velocity (ft/sec)	Applied velocity (m/sec)	Applied velocity (L/sec)	Time fatigue (min)	Tail beats (min)	Corrected velocity (m/sec)
55.2	45.7	6.3	13.0	1925	4.70	1.43	2.59	9.0	-	2.02
54.1	43.8	6.2	11.5	1808	3.05	0.93	1.69	480	162	1.38
58.1	46.9	6.9	13.0	2330	3.00	0.92	1.58	600	170	1.37
55.7	46.2	6.3	12.6	1897	4.70	1.43	2.57	2.3	-	2.02
57.1	46.5	6.4	12.8	210	4.80	1.46	2.52	10.3	-	2.04
57.2	46.7	6.9	12.3	2139	4.70	1.43	2.51	5.0	-	2.02
54.4	44.4	6.4	12.3	1930	4.70	1.43	2.64	1.2	-	2.02
53.2	43.6	5.7	11.8	1810	4.70	1.43	2.70	8.4	-	2.02
57.4	47.4	6.7	13.3	2352	5.70	1.74	2.97	1.3	-	2.38
54.0	44.4	7.1	11.4	1812	4.50	1.37	2.54	6.5	-	1.91
56.9	45.8	7.4	12.0	2070	3.05	0.93	1.61	600	160	1.38
57.8	46.4	7.1	13.2	2347	3.05	0.93	1.58	240	196	1.38
53.4	43.8	5.6	12.0	1745	4.05	1.24	2.28	600	220	1.77
51.5	43.2	6.4	11.5	1596	3.05	0.93	1.77	75.0	170	1.38
53.4	45.7	5.7	12.1	1759	2.50	0.76	1.53	90.0	162	1.16
59.6	47.5	6.5	13.3	2229	3.05	0.93	2.56	5.5	178	1.38
55.4	45.5	6.5	12.5	1432	2.50	0.76	1.37	190	150	1.16
58.0	50.0	6.6	13.1	2213	4.05	1.24	2.13	5.4	214	1.77
57.5	47.2	5.8	12.2	1998	4.05	1.24	2.15	15.1	210	1.77
60.7	47.1	6.4	15.6	2358	3.55	1.08	1.78	59.0	190	1.57
56.5	49.6	6.4	12.3	1903	4.05	1.24	2.18	2.3	220	1.77
53.6	44.2	6.8	12.0	1748	4.05	1.24	2.30	4.1	-	1.77
57.6	47.7	6.2	13.3	2365	3.55	1.08	1.88	90	154	1.57
58.1	46.3	7.0	12.3	2189	3.55	1.08	1.86	430	-	1.57
54.3	48.1	6.5	11.7	1740	2.55	0.78	1.43	30.0	160	1.19
54.2	45.9	6.2	12.0	2010	3.55	1.08	2.00	120	-	1.57
52.5	43.4	5.7	10.8	1662	2.50	0.76	1.48	435	-	1.16
56.5	45.3	7.0	12.0	2040	4.05	1.24	2.18	30.0	-	1.77
58.4	52.3	6.8	13.5	2364	3.05	0.93	1.59	195	-	1.38
55.5	44.8	7.0	12.2	2015	3.05	0.93	1.67	45	-	1.38
54.9	44.3	6.5	11.9	1763	2.55	0.78	1.41	600	-	1.19

Table 1 (cont'd)

Total length (cm)	Standard length (cm)	Maximum width (cm)	Maximum depth (cm)	Weight (g)	Applied velocity			Time fatigue (min)	Tail beats (min)	Corrected velocity (m/sec)
					(ft/sec)	(m/sec)	(L/sec)			
53.2	42.8	7.0	12.0	1910	4.05	1.24	2.32	85	-	1.77
53.5	43.5	6.6	12.5	1786	2.50	0.76	1.45	225	-	1.16
52.8	44.4	6.1	11.1	1382	3.55	1.08	2.05	180	-	1.57
51.8	42.5	5.5	11.5	1569	3.55	1.08	2.09	510	-	1.57
55.3	44.8	5.5	12.6	2052	2.50	0.76	1.40	150	-	1.16
52.2	43.6	5.5	10.0	1449	2.50	0.76	1.49	600	-	1.16
50.9	41.1	7.8	11.6	1587	4.22	1.29	2.53	3.3	200	1.83
53.8	46.8	7.1	11.8	1698	4.22	1.29	2.39	12.3	-	1.83
52.8	43.2	6.6	11.6	1682	4.05	1.24	2.34	41.2	-	1.77
53.0	43.5	5.5	12.2	1918	3.05	0.93	1.75	200	-	1.38
57.8	46.8	7.2	13.1	2292	4.05	1.24	2.14	31.1	-	1.77
49.3	40.2	5.5	10.3	1304	3.55	1.08	2.19	2.0	-	1.57
54.6	44.4	7.2	12.1	1918	3.55	1.08	1.98	53.0	-	1.57
54.8	44.0	7.1	12.9	2026	3.55	1.08	1.97	600	160	1.57
53.0	42.5	6.3	12.6	1728	2.50	0.76	1.47	75.0	-	1.16
53.0	44.0	6.6	11.3	1673	4.22	1.29	2.43	7.2	196	1.83
54.0	44.0	7.2	11.9	1869	3.55	1.08	2.00	19.3	-	1.57
53.8	44.1	6.7	12.0	1965	3.55	1.08	2.00	5.1	-	1.57
49.3	41.4	5.5	10.2	1336	2.55	0.78	1.58	600	160	1.19
54.8	44.2	6.6	11.8	1872	4.05	1.24	2.25	135	240	1.77
49.4	39.2	5.5	10.1	1189	3.05	0.93	1.88	45	-	1.38
54.2	45.8	6.4	11.6	1821	3.05	0.93	1.71	80	-	1.38
56.9	46.2	6.3	13.4	2217	3.55	1.08	1.90	25	220	1.57
57.0	46.0	7.6	13.1	2223	4.05	1.24	2.17	9.6	-	1.77
56.0	45.5	7.8	13.0	2163	4.05	1.24	2.20	21.1	-	1.77
54.7	44.2	7.3	12.6	1889	3.55	1.08	1.98	7.4	-	1.57
52.7	42.7	6.4	10.9	1626	3.55	1.08	2.54	600	-	1.57
53.5	44.2	6.5	11.7	1854	2.50	0.76	1.42	600	162	1.16
52.5	42.9	7.4	11.8	1826	5.05	1.54	2.93	2.4	-	2.15
54.5	44.1	7.0	12.3	1917	3.00	0.92	1.70	600	-	1.36
57.1	45.7	7.2	12.8	2080	4.05	1.24	2.16	15.3	-	1.77
57.2	45.5	7.3	13.0	2214	3.50	1.05	1.86	600	200	1.53

Table 1 (cont'd)

Total length (cm)	Standard length (cm)	Maximum width (cm)	Maximum depth (cm)	Weight (g)	Applied velocity (ft/sec)	Applied velocity (m/sec)	Applied velocity (L/sec)	Time fatigue (min)	Tail beats (min)	Corrected velocity (m/sec)
57.6	45.8	7.2	12.1	2134	5.05	1.54	2.67	3.5	-	2.15
59.1	48.0	6.4	13.2	1807	4.70	1.43	2.42	2.1	-	2.02
56.5	45.8	6.6	12.1	2060	4.05	1.24	2.18	19.1	-	1.77
57.8	46.3	6.8	12.6	2153	4.05	1.24	2.13	4.5	-	1.77
55.6	44.6	6.1	12.2	1705	4.05	1.24	2.22	13.2	-	1.77
Mean =: 54.98	45.06	6.56	12.19	1878.8						
S.D. =: 2.45	2.16	0.60	0.90	356.3						
S.E. =: 0.30	0.26	0.07	0.11	43.2						

Table 2. Length-weight relations, swimming speeds and time-to-fatigue for adult sockeye salmon tested at 18°C. Corrected velocities as in Table 1.

Total length (cm)	Standard length (cm)	Maximum width (cm)	Maximum depth (cm)	Weight (g)	Applied velocity (ft/sec)	Applied velocity (m/sec)	Applied velocity (L/sec)	Fatigue time (min)	Tail beats (min)	Corrected velocity (m/sec)	Sex
55.0	46.3	-	-	1603	2.06	0.63	1.14	600	-	0.98	F.
52.5	43.5	-	-	1604	3.05	0.93	1.77	600	184	1.38	F
50.5	42.1	-	-	1330	3.05	0.93	1.84	600	178	1.38	F
53.9	44.3	-	-	1762	4.05	1.24	2.29	34.5	220	1.77	M
48.2	43.0	-	-	1498	4.05	1.24	2.56	22.5	200	1.77	F
52.4	43.4	-	-	1604	4.05	1.24	2.35	84.5	204	1.77	M
51.0	42.8	-	-	1565	3.05	0.93	1.82	360	-	1.38	F
57.5	47.4	-	-	1843	4.05	1.24	2.15	600	206	1.77	M
50.1	41.2	-	-	1682	3.05	0.93	1.85	180	-	1.38	M
55.4	46.1	-	-	1720	5.39	1.64	2.96	10.2	-	2.23	F
54.5	44.6	-	-	1594	5.39	1.64	3.01	6.3	-	2.23	M
57.1	47.2	-	-	2017	5.39	1.64	2.88	2.9	-	2.23	M
55.7	46.7	-	-	1855	5.39	1.64	2.95	4.1	-	2.23	M
62.1	51.7	-	-	2467	4.70	1.43	2.31	6.9		2.02	F
51.0	42.0	-	-	1438	3.05	0.93	1.82	360	180	1.38	F
53.5	44.4	-	-	1617	4.70	1.43	2.68	100	226	2.02	F
59.9	48.3	-	-	2233	3.05	0.93	1.55	600	176	1.38	M
56.5	46.5	-	-	1837	5.39	1.64	2.91	4.5	-	2.23	M
61.1	50.2	-	-	2441	5.39	1.64	2.69	6.0	-	2.23	F
56.0	47.4	-	-	1782	4.70	1.43	2.56	20.6	-	2.02	F
54.0	45.0	-	-	1692	3.55	1.08	2.00	60	-	1.56	M
54.5	44.3	-	-	1952	3.55	1.08	1.98	195	-	1.56	F
57.1	46.8	-	-	1955	3.55	1.08	1.89	600	160	1.56	F
58.3	48.3	-	-	1975	3.55	1.08	1.85	600	-	1.56	F
54.5	45.2	-	-	1703	3.55	1.08	1.98	240	-	1.56	F
53.0	43.0	-	-	1731	3.55	1.08	2.04	150	-	1.56	M
51.0	42.3	-	-	1560	3.55	1.08	2.12	45.0	-	1.56	F
52.6	43.3	-	-	2017	3.05	0.93	1.77	300	172	1.38	M
54.6	44.6	6.1	11.1	1778	2.60	0.79	1.45	300	150	1.22	M
53.6	43.9	-	-	1876	3.05	0.93	1.73	90.0	-	1.38	M
54.4	45.7	7.0	11.4	1913	2.60	0.79	1.48	600	148	1.22	F
53.0	43.9	6.1	10.8	1593	2.60	0.79	1.49	600	160	1.22	F

Table 2 (cont'd)

Total length (cm)	Standard length (cm)	Maximum width (cm)	Maximum depth (cm)	Weight (g)	Applied velocity (ft/sec)	Applied velocity (m/sec)	Applied velocity (L/sec)	Fatigue time (min)	Tail beats (min)	Corrected velocity (m/sec)	Sex
53.3	44.6	6.9	11.3	1850	3.50	1.07	2.00	90.0	-	1.55	F
53.6	44.6	6.3	10.9	1627	3.50	1.07	1.99	600	-	1.55	M
51.5	43.0	6.3	11.1	1666	3.50	1.07	2.07	600	180	1.55	M
51.5	42.2	6.0	10.0	1369	4.05	1.24	2.40	150	200	1.77	F
56.7	46.0	6.6	11.1	1988	4.05	1.24	2.18	60.0	-	1.77	M
56.1	46.8	6.8	11.2	1875	3.50	1.07	1.90	105	-	1.55	M
56.7	46.2	6.4	10.5	1805	3.50	1.07	1.88	20.0	144	1.55	M
53.2	44.9	6.5	11.4	1789	3.50	1.07	2.00	40.0	-	1.55	F
54.0	44.7	6.5	10.6	1658	5.50	1.68	3.10	4.7	-	2.25	F
52.6	43.4	6.3	10.5	1684	5.00	1.53	2.90	19.3	-	2.14	F
55.8	45.7	6.4	10.8	1779	5.56	1.70	3.04	2.0	-	2.37	F
54.5	44.6	6.3	10.5	1634	4.70	1.43	2.63	68.2	202	2.02	M
50.4	41.4	6.0	10.0	1331	4.70	1.43	2.84	16.0	202	2.02	M
56.8	47.4	6.6	11.3	1990	5.60	1.70	3.00	3.6	-	2.37	F
50.2	42.1	5.8	9.7	1325	5.05	1.54	3.07	11.8	-	2.14	F
50.1	45.4	6.1	10.0	1401	4.20	1.28	2.55	94.7	188	1.82	M
55.1	46.2	7.1	11.2	1893	4.70	1.43	2.60	4.6	-	2.02	F
52.4	47.1	6.2	11.2	1672	4.20	1.28	2.44	85.7	-	1.82	F
55.4	46.1	6.5	11.4	1852	4.00	1.22	2.20	425	184	1.76	F
51.1	42.8	6.0	10.2	1518	5.20	1.59	3.10	3.5	-	2.23	F
52.4	43.0	6.7	10.8	1725	2.00	0.61	1.16	600	-	0.96	F
53.2	43.8	6.7	11.2	1851	2.00	0.61	1.14	600	-	0.96	F
Mean =:											
54.02	44.95	6.41	10.81	1750.4							
SD =:											
2.79	2.16	0.33	0.50	237.3							
SE =:											
0.34	0.29	0.07	0.10	32.3							

FIGURES

Fig. 1. Typical velocity fatigue curve for a salmonid. Time-to-fatigue is expressed on a linear scale in (A) and a logarithmic scale in (B). Duration of test was 600 min, using sockeye fingerlings of nominal 19 cm total length and 50 g wet weight at 10°C (Brett 1964). Velocity is expressed in fish lengths per second (L/sec). Points are for similar positions in (A) and (B). Sustained speeds occur anywhere from zero to the maximum sustained at 54 cm/sec (2.8 L/sec). Prolonged speeds result in fatigue occurring anywhere from 300 min to 0.3 min according to increasing velocity from 54 cm/sec to 90 cm/sec (4.7 L/sec). Burst speeds can only be maintained for about 20 sec or less--up to about 190 cm/sec (10 L/sec).

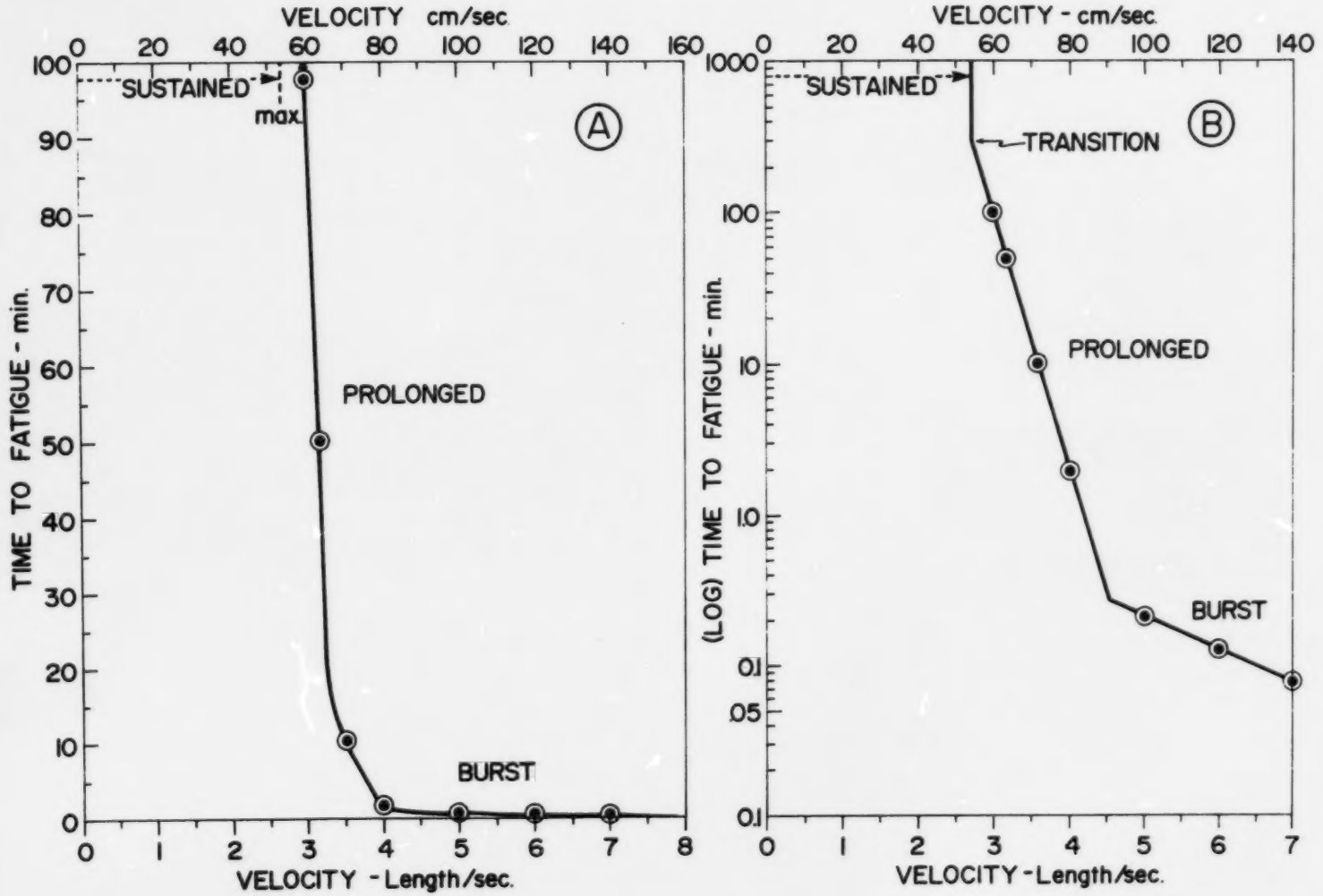

VELOCITY cm/sec
0 20 40 60 80 100 120 140 160
100
90
80
70
60
50
40
30
20
10
0
SUSTAINED
max.
A
PROLONGED
BURST
TIME TO FATIGUE - min.
0 1 2 3 4 5 6 7 8
VELOCITY - Length/sec.
VELOCITY - cm/sec.
0 20 40 60 80 100 120 140
1000
100
10
1.0
0.1
0.05
0.1
SUSTAINED
TRANSITION
B
PROLONGED
BURST
(LOG) TIME TO FATIGUE - min.
0 1 2 3 4 5 6 7
VELOCITY - Length/sec.

Fig. 2. View of 27 cm OD steel pipe used as swimming tunnel for adult sockeye and pink salmon. Upstream end passes through bottom stoplog of dam. Pipe runs alongside Robertson Creek concrete flume. Fish chamber was located in walled-off section, here shown with two wall panels removed. Downstream valve is wide open. Fish holding tanks can be seen at upper and lower ends of the tunnel.

FLUME
FISH TANKS
FISH CHAMBER
CONTROL VALVE

Fig. 3. Downstream butterfly valve showing control arm with calibrated positions for fixed velocities up to 280 cm/sec.

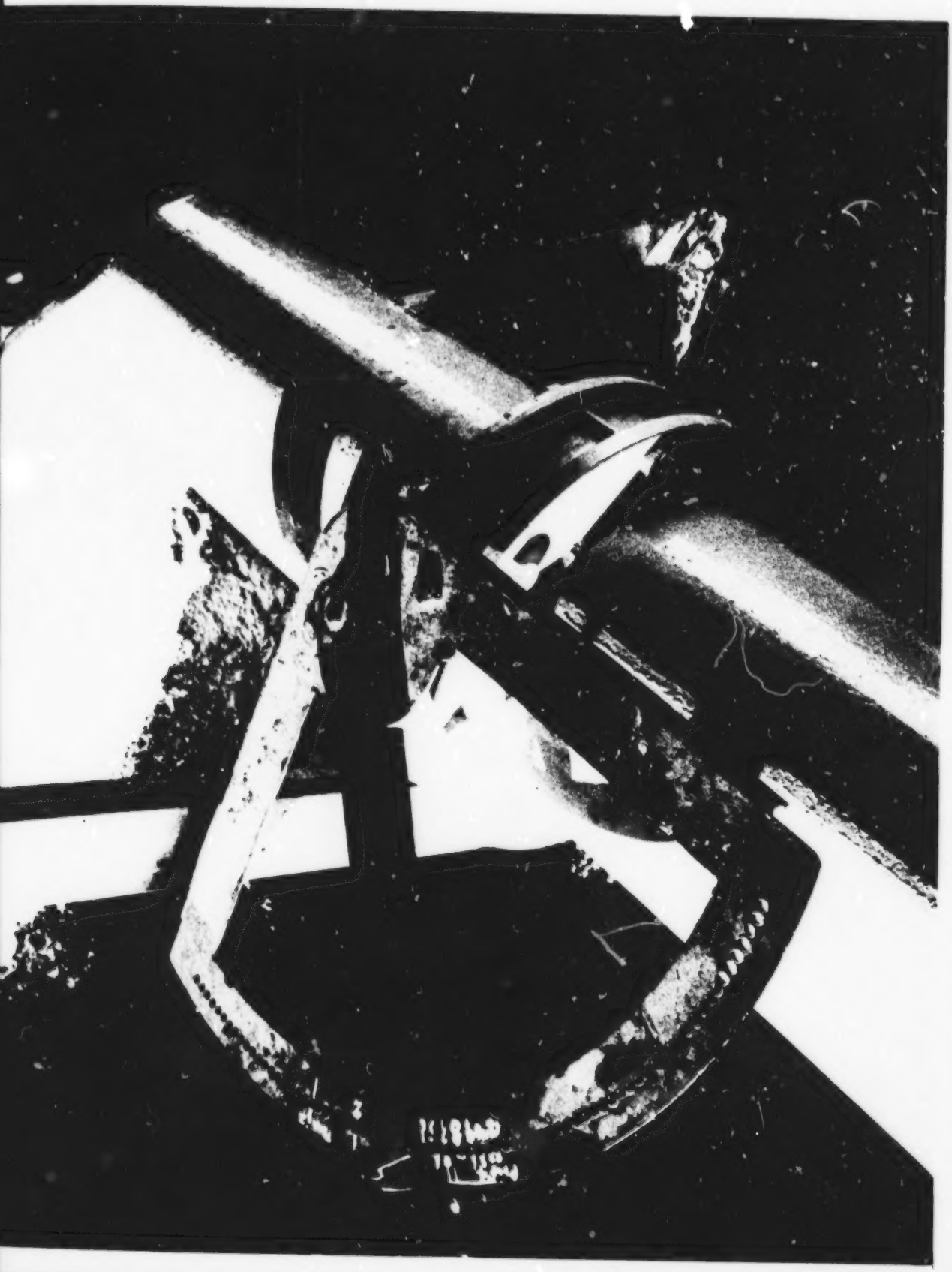


Fig. 4. Fish chamber section of water tunnel with hatch open. A 25 inch (63.5 cm) rule is located just below the opening. An electric charge (5-10 V, AC) was applied to the downstream aluminum vanes embedded in a fibreglass section. Similar vanes (not charged) prevented upstream movement. Free movement within the chamber was 150 cm long.

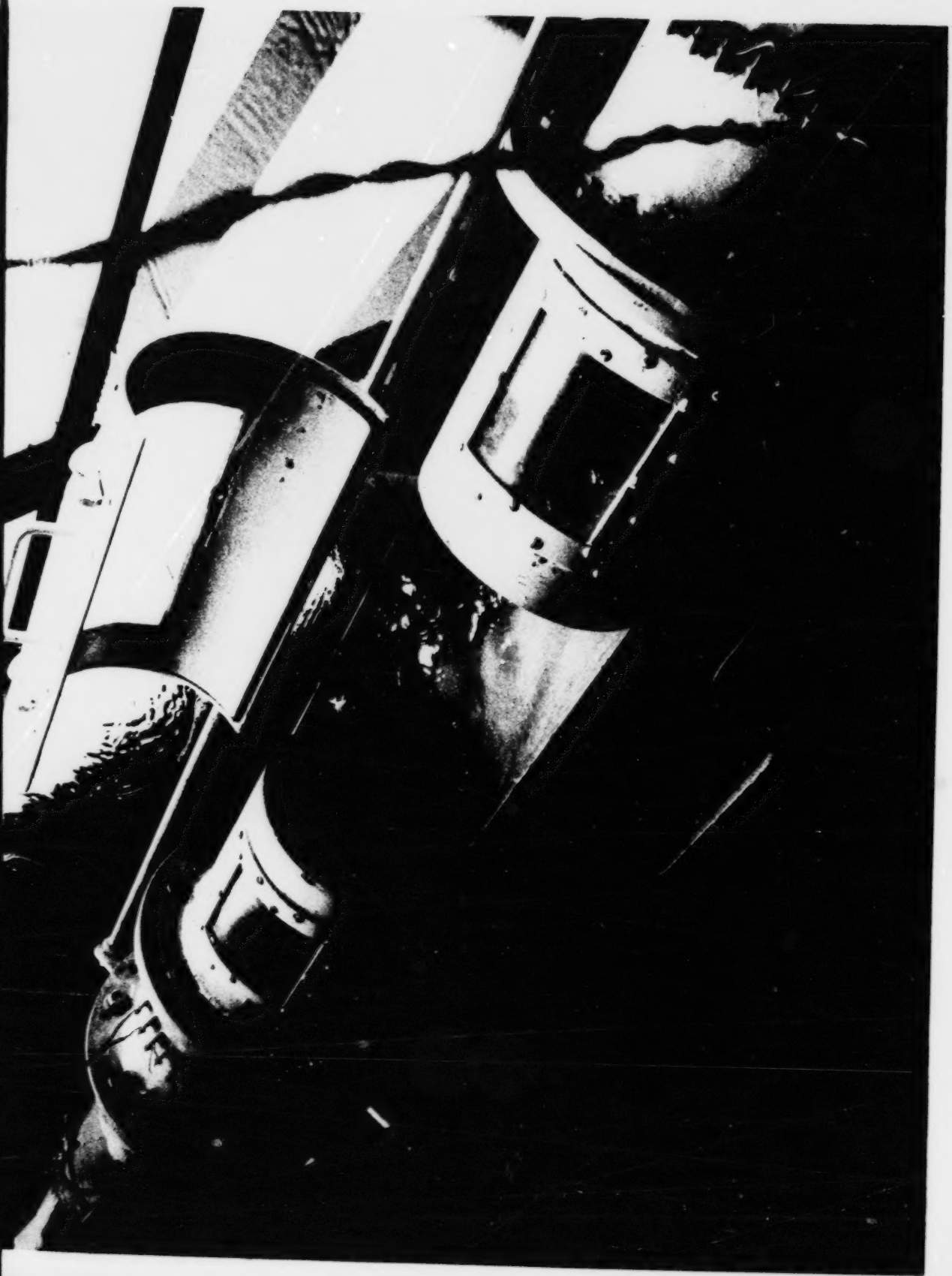
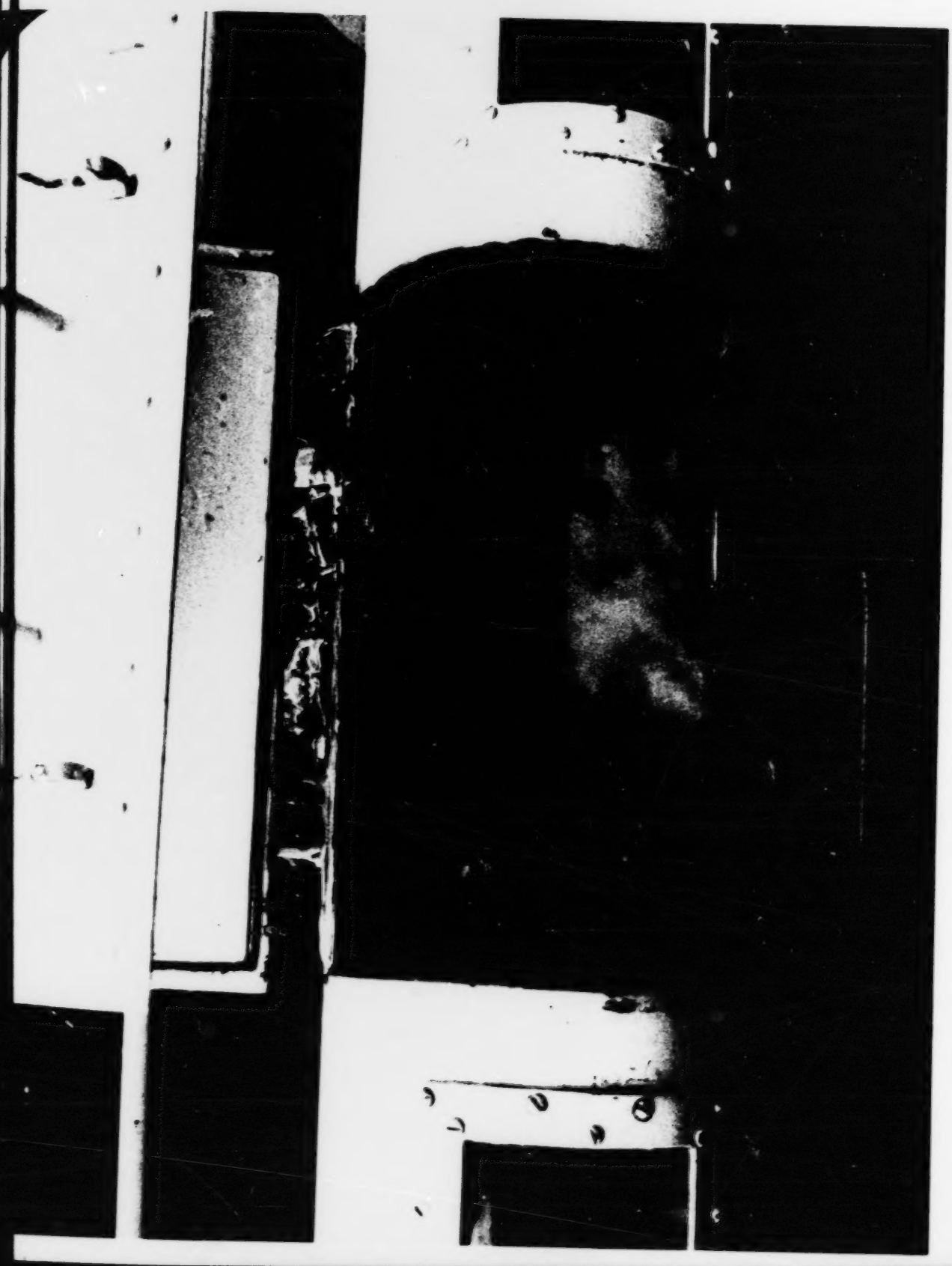


Fig. 5. Adult pink salmon, 55 cm total length, resting in quiet water following a 10-hr fatigue test. Hatch open with flushing water spilling over far edge.



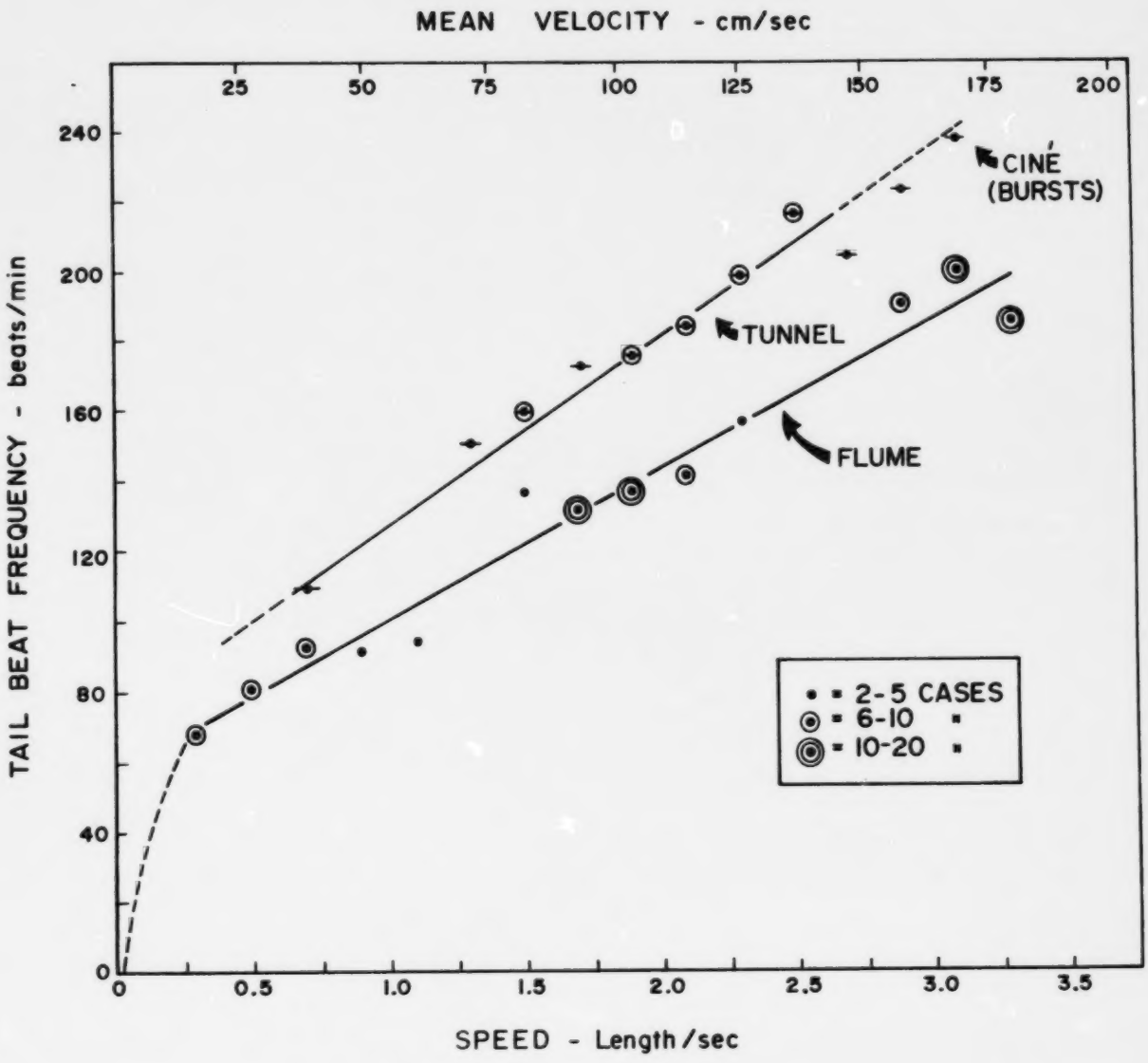


Fig. 6. The relation of tailbeat frequency to swimming speed of sockeye salmon in a flume (184 cm wide) and in the steel tunnel (25 cm ID). Maximum sustained beats averaged 220/min. Ciné camera was used for counts of 200/min and above, frequently involving short bursts. Mean velocity determined for an average length of sockeye equal to 54 cm. Beats below about 60/min are accompanied by a change in amplitude resulting in a marked change of slope at this general threshold.

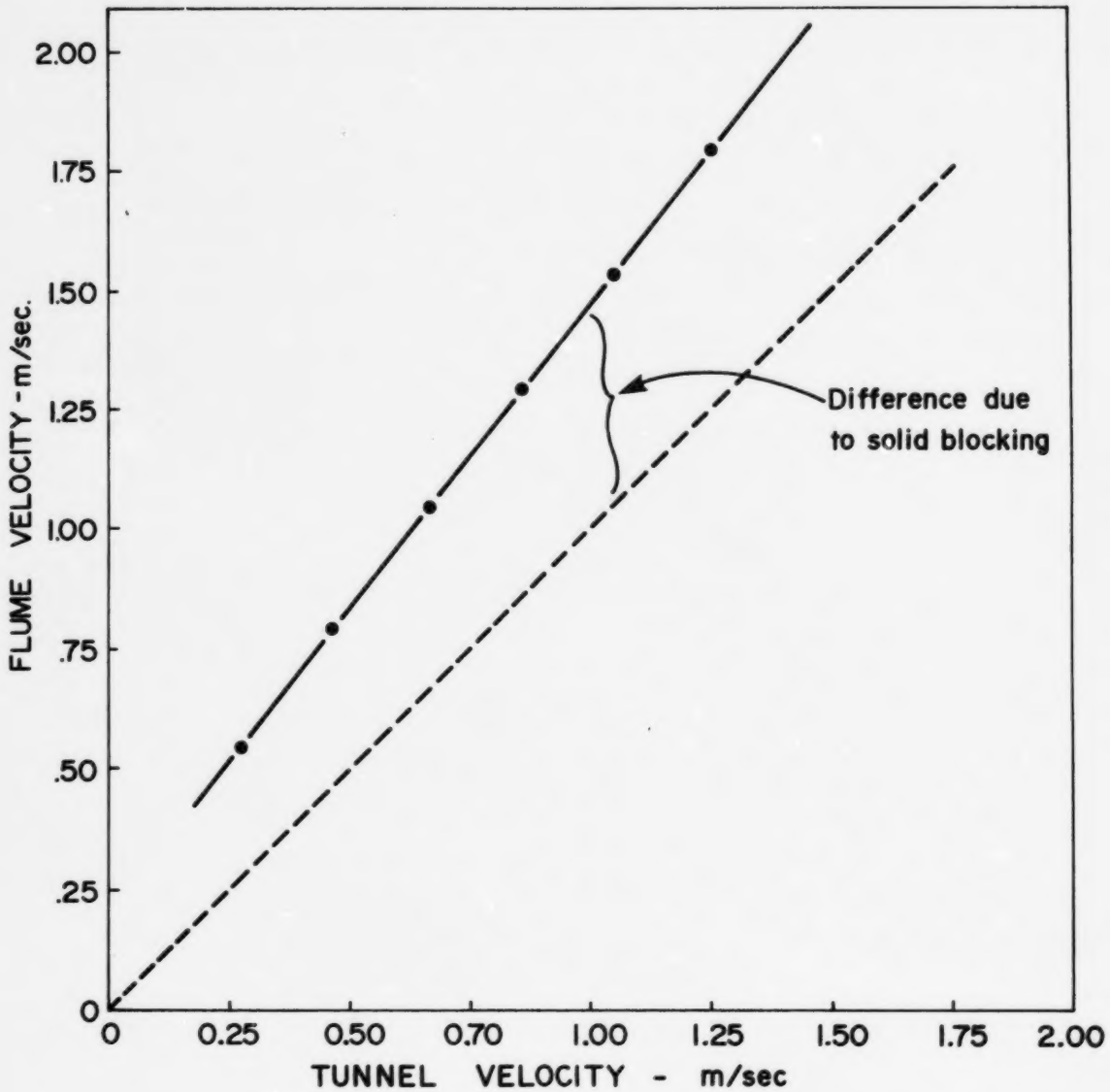


Fig. 7. Relation between tunnel velocity and flume velocity, according to equal tail-beat frequencies of adult sockeye salmon--derived from data in Fig. 6. Tunnel restriction due to solid blocking from maximum cross-section of fish occupying approximately 12% of cross-section of tunnel. Dotted line is geometric loci of equal velocity points, which would have occurred in the absence of any blocking.

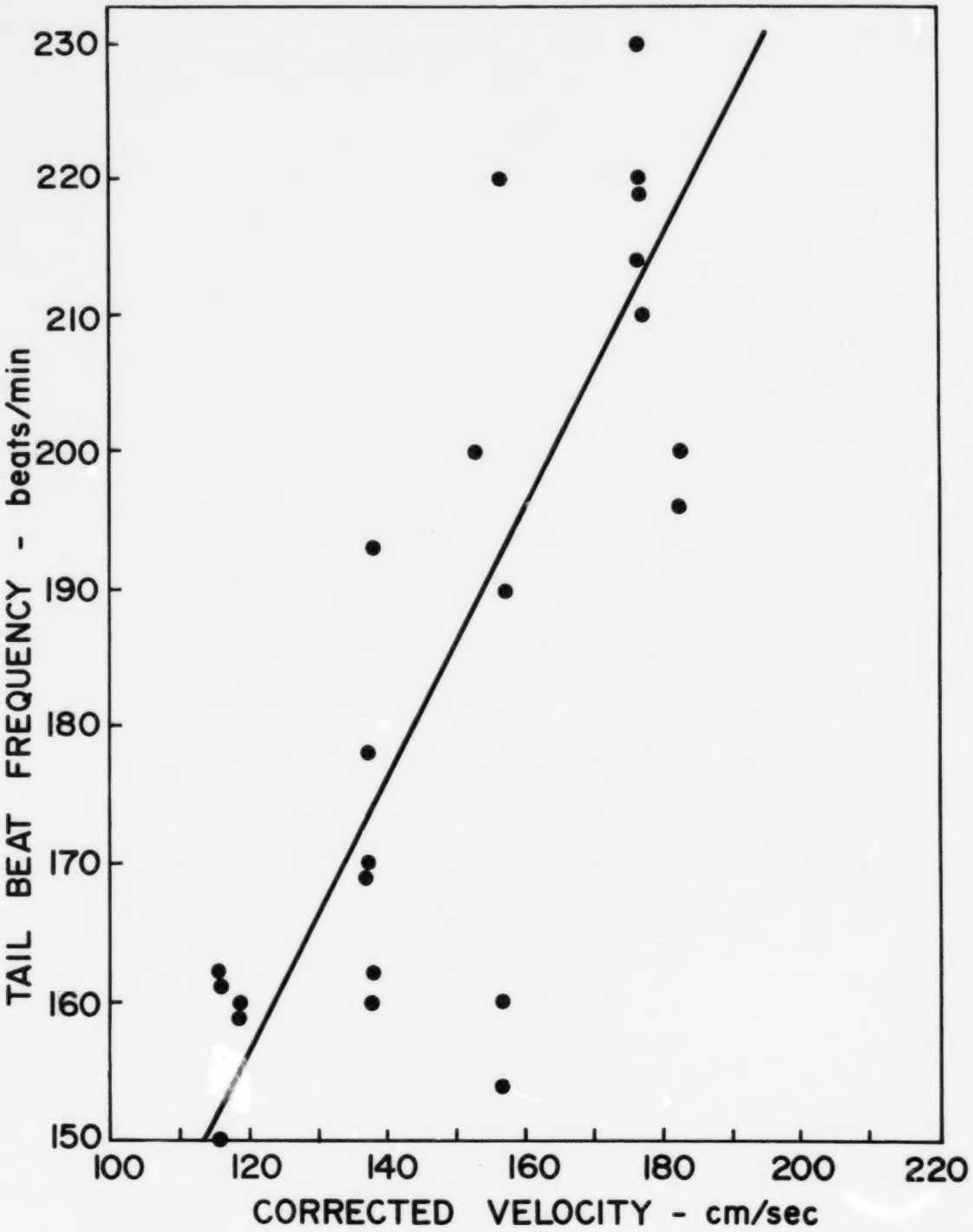


Fig. 8. Relation of tail-beat frequency of adult pink salmon to velocity corrected for solid blocking. Mean total length = 55 cm. Beats below 200/min were counted directly by eye; those above were from cine' film records.

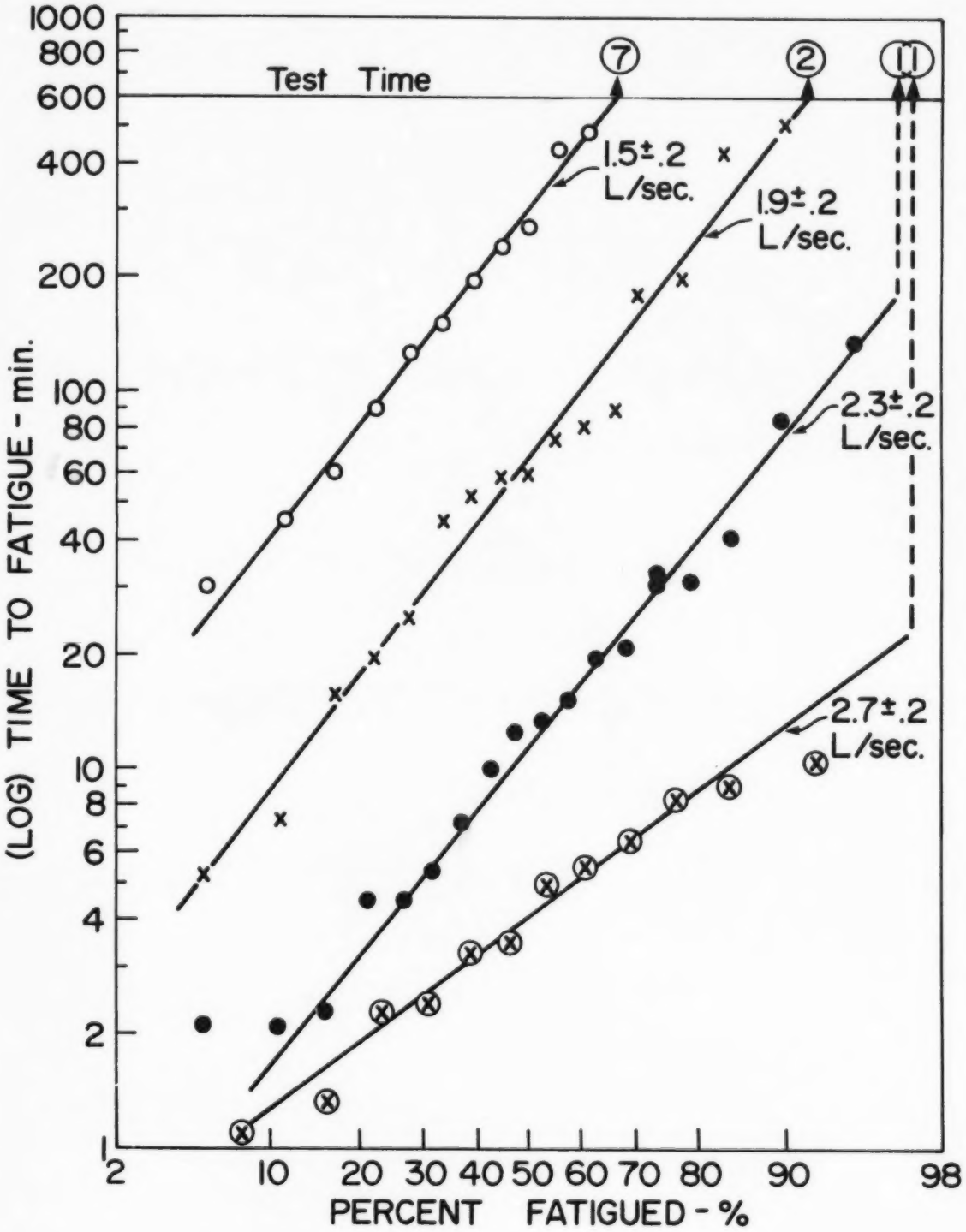


Fig. 9. Relation of fatigue time (log) to order of fatigue (percent in probits) for adult pink salmon of mean total length (L) = 55 cm. Fish grouped in four velocity intervals in terms of L/sec. Circled numbers represent fish still swimming at end of test time (10 hr).

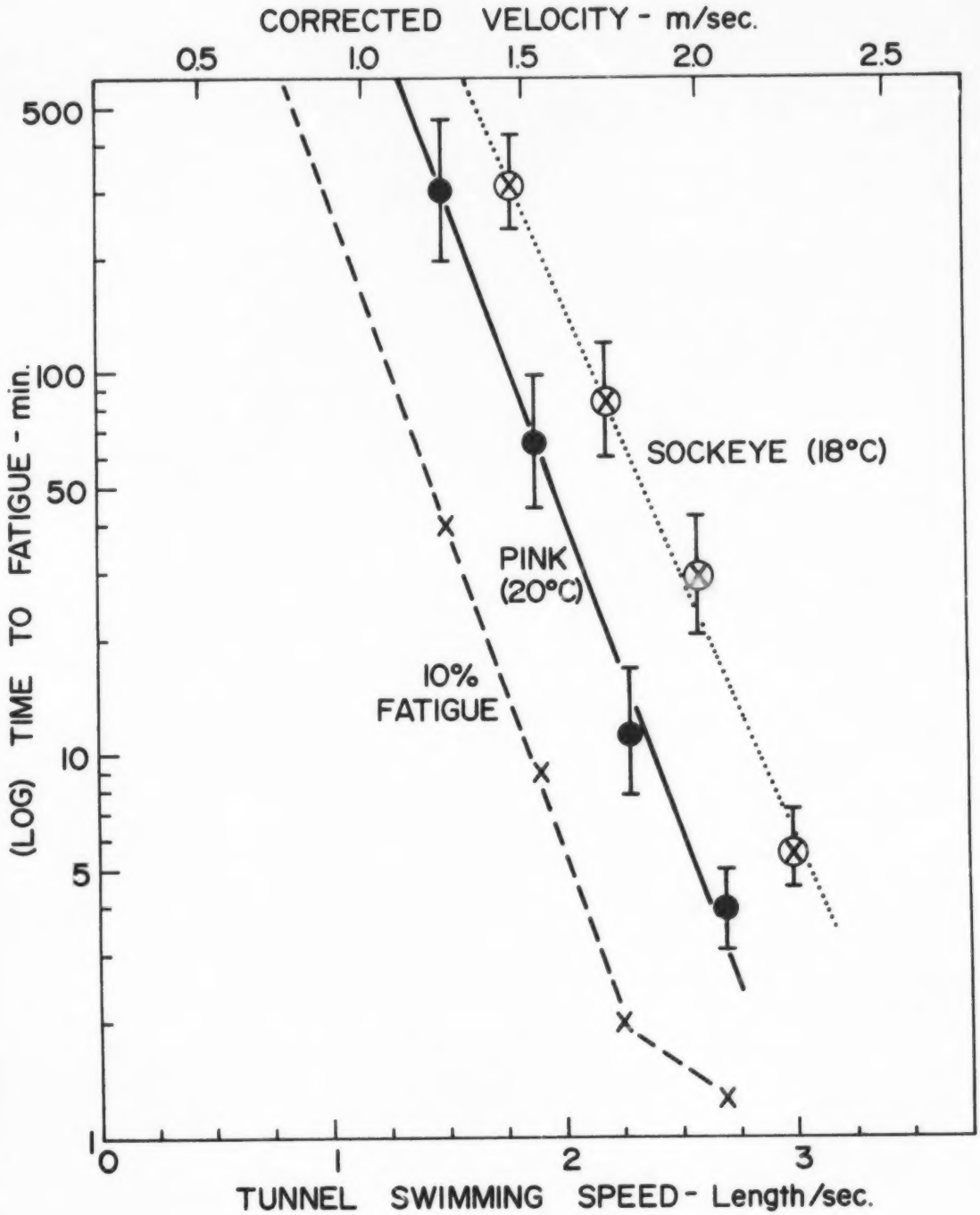


Fig. 10. Relation between mean fatigue time (±SE) and swimming speed (L/sec) of adult pink salmon (length = 55 cm) and sockeye salmon (length = 54 cm) in a 25-cm ID water tunnel. Time-to-50%-fatigue approximates mean fatigue time (from probit plot, Fig. 9). Time for the first 10% of pink salmon to fatigue shown as broken line. Data analysis for sockeye from Brett (1967). Swimming speeds (m/sec) corrected for blocking effect of tunnel (see text).

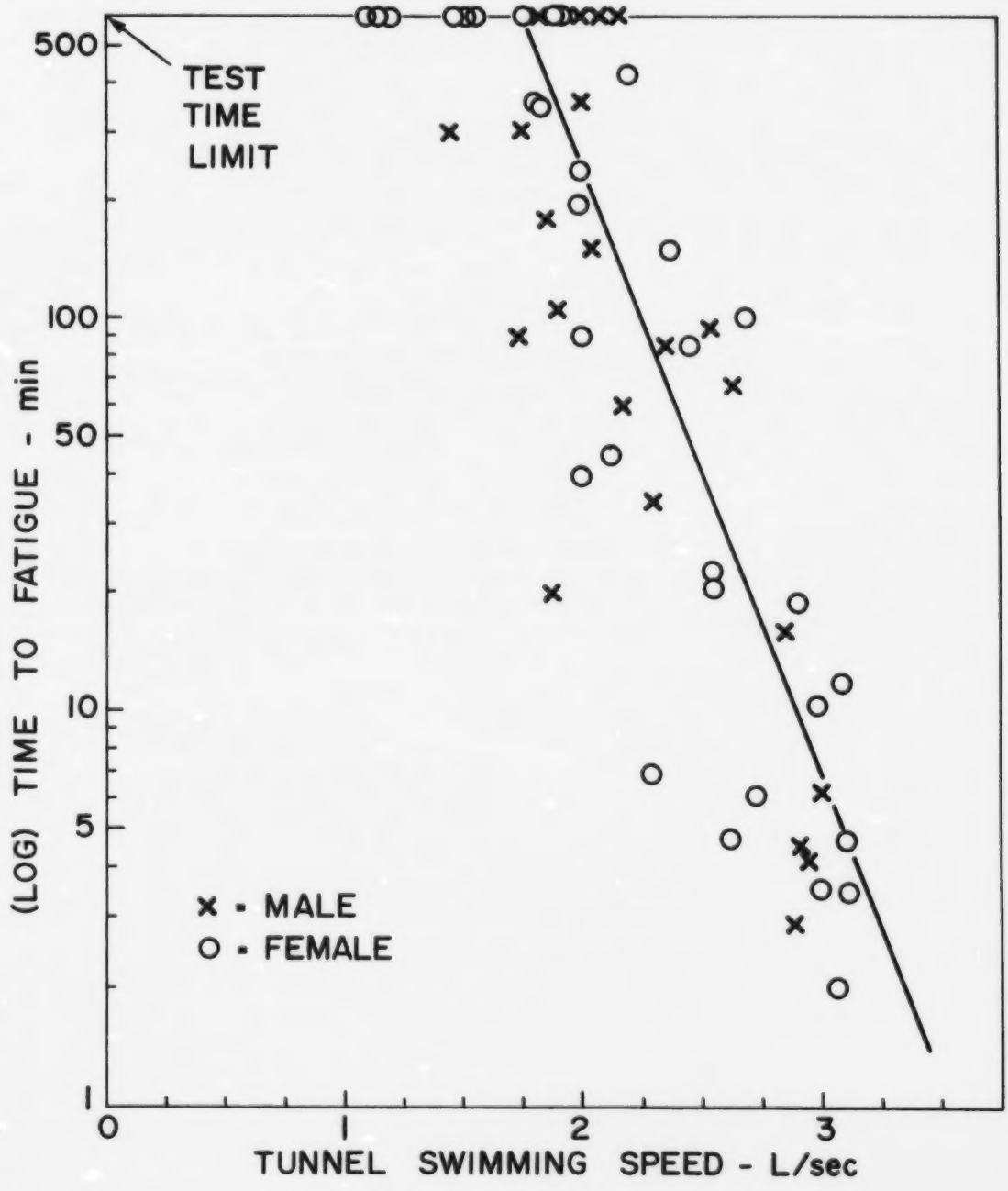
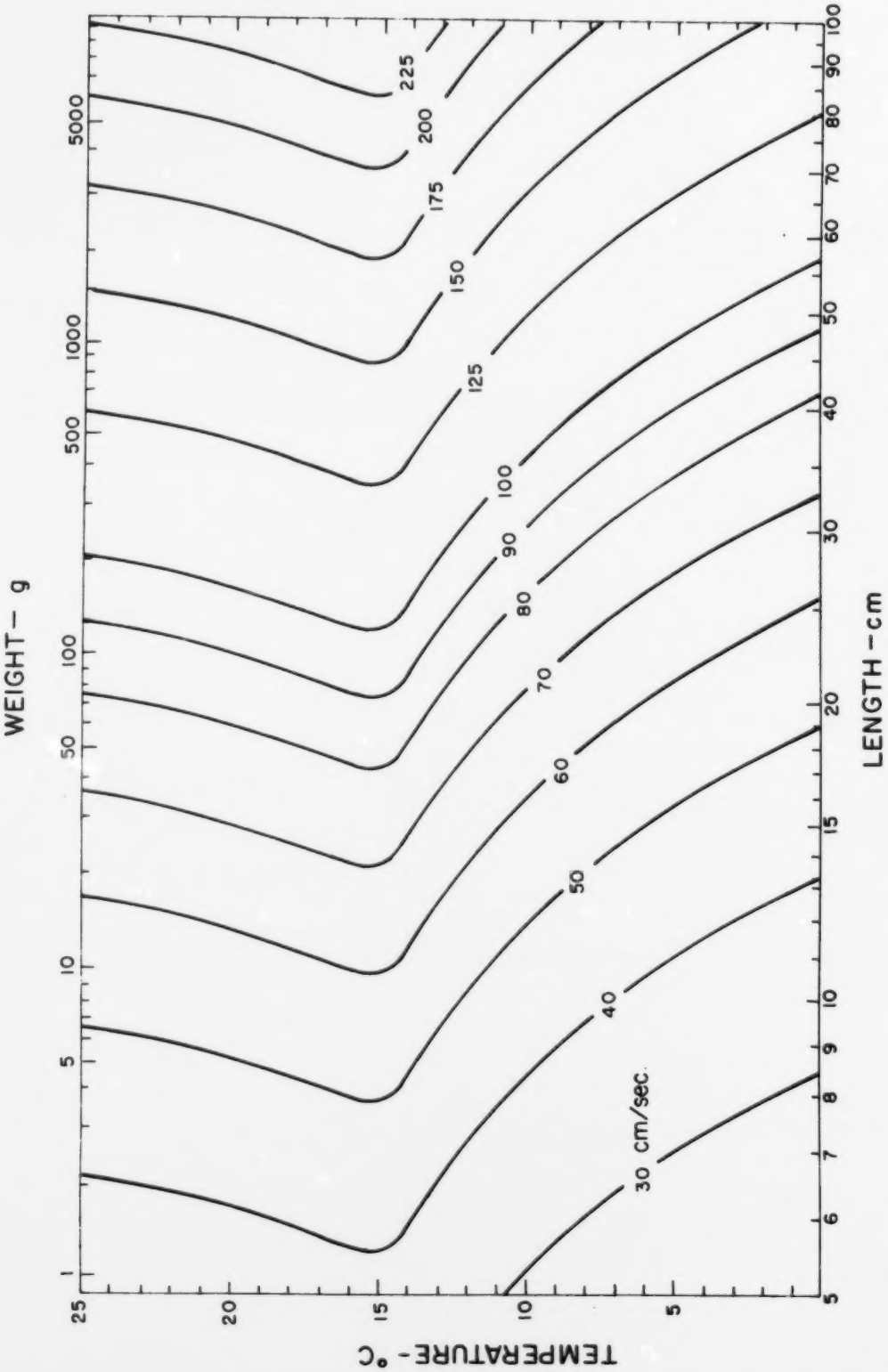


Fig. 11. Similar relation as Fig. 10 for adult sockeye salmon but plotted as individual data points for males and females. Line taken from Fig. 10. Swimming speeds not corrected for tunnel effect.

Fig. 12. Temperature-size response surface for maximum 60-min prolonged speed of sockeye salmon represented by isopleths for selected speeds in cm/sec (from Brett and Glass 1973). Adult pink salmon (55 cm length) perform at about 0.8 times the speed of sockeye.


WEIGHT - g
1
5
10
50
100
500
1000
5000
TEMPERATURE - °C
25
20
15
10
5
LENGTH - cm
5
6
7
8
9
10
15
20
30
40
50
60
70
80
90
100
30 cm/sec
40
50
60
70
80
90
100
125
150
175
200
225